

**LLNL CALIBRATION PROGRAM: DATA COLLECTION, GROUND TRUTH VALIDATION, AND REGIONAL CODA MAGNITUDE**

Stephen C. Myers, Kevin Mayeda, William R. Walter, Craig A. Schultz, Jennifer L. O'Boyle, Abraham Hofstetter\*, Arthur J. Rodgers, and Stanley D. Ruppert

Lawrence Livermore National Laboratory, Geophysical Institute of Israel\*

Sponsored by National Nuclear Security Administration  
Office of Nonproliferation Research and Engineering  
Office of Defense Nuclear Nonproliferation

Contract No. W-7405-ENG-48

**ABSTRACT**

Lawrence Livermore National Laboratory (LLNL) integrates and collects data for use in calibration of seismic detection, location, and identification. Calibration data are collected by 1) numerous seismic field efforts, many conducted under National Nuclear Security Administration (NNSA) Research Opportunity Announcement (ROA) and Defense Threat Reduction Agency (DTRA) Program Research and Development Announcement (PRDA) contracts, and 2) permanent seismic stations that are operated by national and international organizations. Local-network operators and international organizations (e.g. International Seismic Centre) provide location and other source characterization (collectively referred to as source parameters) to LLNL, or LLNL determines these parameters from raw data. For each seismic event, LLNL rigorously characterizes the uncertainty of source parameters. This validation process is used to identify events whose source parameters are accurate enough for use in calibration.

LLNL has developed criteria for determining the accuracy of seismic locations and methods to characterize the covariance of calibration data sets. Although the most desirable calibration events are chemical and nuclear explosions with highly accurate locations and origin times, catalogues of naturally occurring earthquakes offer needed geographic coverage that is not provided by man-made sources. The issue in using seismically determined locations for calibration is validating the location accuracy. Sweeney (1998) presented a 50/90 teleseismic, network-coverage criterion (50 defining phases and 90° maximum azimuthal gap) that generally results in 15-km maximum epicenter error. We have also conducted tests of recently proposed local/regional criteria and found that 10-km accuracy can be achieved by applying a 20/90 criterion. We continue to conduct tests that may validate less stringent criteria (which will produce more calibration events) while maintaining desirable location accuracy. Lastly, we examine methods of characterizing the covariance structure of calibration data sets. Each data set is likely to be affected by distinct error processes that result in a distinct covariance structure. We present covariance models for select data sets and demonstrate how these data sets can be integrated into one calibration-event catalog.

LLNL has developed a robust magnitude calibration methodology for sparsely distributed regional stations using narrow band coda envelopes. This technique provides stable magnitudes for small events that make detection and identification calibration possible at low magnitudes. This approach has most recently been applied to International Monitoring System (IMS) stations located in Israel, Jordan and Egypt for events that span local and near regional distances. Our preliminary results show that a magnitude estimate from one station using the coda is equivalent to a network average of roughly 9 stations when using traditional magnitudes (e.g.,  $m_b(P)$ ,  $M_L$ ,  $M_d$ ). The stability of the coda comes from measuring a long length of coda using a calibrated synthetic envelope as an empirical metric. We relate the non-dimensional coda amplitudes to an absolute scale by tying them to independent moment estimates from larger waveform-modeled events. Unlike most narrow band magnitudes, this approach yields an azimuthally averaged, moment-rate spectrum that is completely corrected for path and site effects. The resultant magnitudes from the spectra (e.g.,  $M_w$  and  $m_b$ ) are fully transportable and do not suffer from regional bias.

**KEY WORDS:** calibration events, event location, coda magnitudes, validation.

## **OBJECTIVE**

### **Introduction**

Lawrence Livermore National Laboratory's (LLNL's) seismic calibration program aims to improve prediction of both earth-model-based parameters – such as path-dependent travel time and amplitude – and subsequently determined source parameters – such as location and magnitude. An important component of this effort is the integration and development of accurate calibration (a.k.a. ground truth [GT]) events, for used in the construction or validation of earth models and empirical corrections (Schultz et al., 1998; Myers and Schultz 2000). In our integration effort we collect calibration events from the seismological community, validate location parameters, and in some instances determine parameters that have not been included by the contributor (e.g. origin time or magnitude). Below, we briefly describe our efforts to collect new calibration data. Then we focus on two of the key methodologies that we use in integration, 1) validation of location parameters, and 2) magnitude determination.

Teaming with numerous groups, LLNL has succeeded in obtaining ROA contracts with the object of developing new calibration events. These efforts focus on collection of calibration events in the European Arctic and the Middle East. In several cases temporary stations will be deployed and mine-related or dedicated explosions will be recorded. In other cases the focus is on passive data collection. These projects will provide calibration data with accurate or fiducial hypocenter parameters and regionally determined magnitudes.

As a complement to LLNL's calibration-event collection efforts, we integrate a large number of events from the general seismic community. Contributors range from local network operators and global catalogs, to event relocations from individual researchers. We find that the accuracy of location parameters from these sources varies significantly, and that a rigorous validation effort is required to characterize the uncertainty of each location parameter. For instance, event locations are usually contributed with formal uncertainties only, requiring an assessment of absolute accuracy. LLNL's work has helped to establish network coverage criteria as a means to assess epicenter accuracy, and our ongoing efforts continue to test these criteria. Below, we discuss epicenter accuracy criteria for teleseismic networks and for local networks.

Event magnitude is a crucial parameter in seismic monitoring, yet many contributed events either do not include magnitude or the magnitude determination is preliminary in nature. For events that are recorded teleseismically, the magnitude is generally reliable, due to the number of reporting stations and relatively low variance amplitude observations. However, events that are only recorded on regional networks are typically unreliable, due to the small number of recording stations and high variance amplitude observations. Therefore, LLNL has developed a stable magnitude method based on coda envelope measurements that can be reliably used even for single-station magnitude determination.

## **RESEARCH ACCOMPLISHED**

### **Seismic Calibration Studies**

LLNL is teamed with a number of organizations – domestic and international, academic and private – through the NNSA ROA contracting mechanism, to conduct calibration studies. Figure 1 shows the number and geographic extent of these projects. Projects range from the European Arctic, Turkey, Saudi Arabia, and a broad Middle East calibration effort.

In the European arctic LLNL is working with partners NORSAR and KRSC on the ROA contract to provide ground truth mining explosions for key stations of the IMS network and other stations of interest in northern Fennoscandia and northwestern Russia. In Turkey LLNL is involved in a project to conduct a calibration explosion in Lake Van that will yield calibration and phenomenological data. Also in Turkey and Israel, we are working with in-country collaborators to implement coda-based magnitudes in the routine production of catalogs. Finally, LLNL is working with collaborators in Saudi Arabia to deploy seismic instrumentation for the purpose of calibration event data collection.

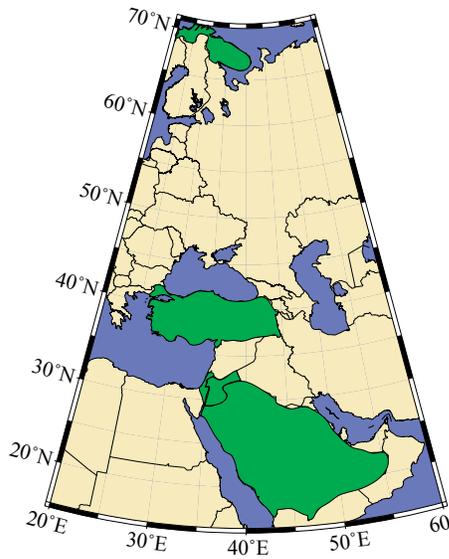


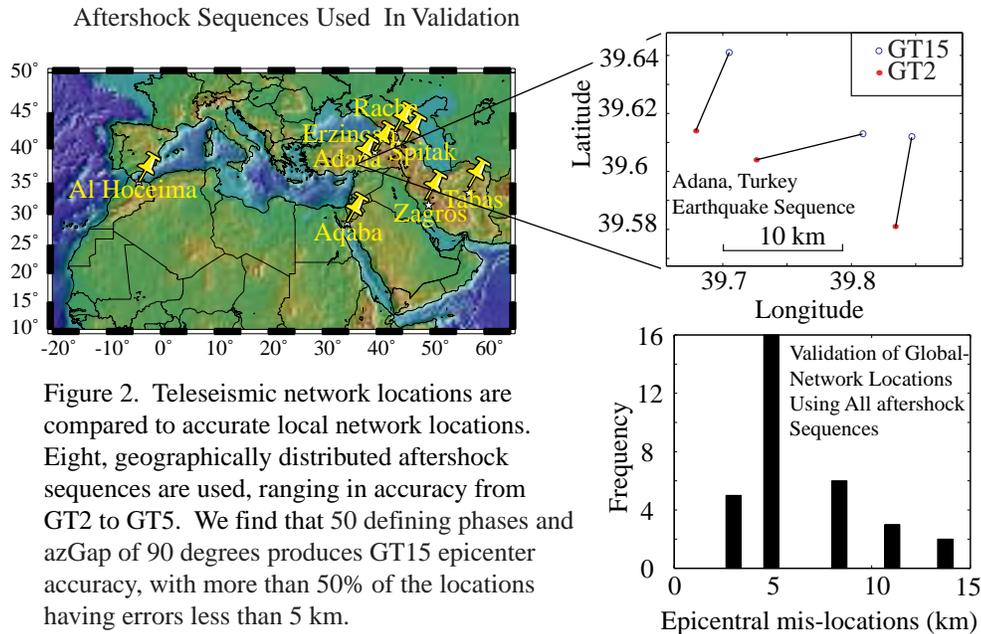
Figure 1. LLNL is involved in collaborative projects in Eurasia and the Middle East. In the European arctic LLNL is working with partners NORSAR and KRSC on the ROA contract to provide ground truth mining explosions for key stations of the IMS network and other stations of interest in northern Fennoscandia and northwestern Russia. In Turkey LLNL is involved in a project to conduct a calibration explosion in Lake Van that will yield calibration and phenomenological data. Also in Turkey and Israel, we are working with in-country collaborators to implement coda-based magnitudes in the routine production of catalogs. Finally, LLNL is working with collaborators in Saudi Arabia to deploy seismic instrumentation for the purpose of calibration event data collection.

### **Epicenter Validation**

Accurate event locations are a cornerstone of travel-time calibration. Standard seismic location uncertainty analysis provides an estimate of location precision, but mislocation due to model-based travel-time prediction uncertainty and bias are typically not included in the uncertainty analysis. Therefore, validation of event accuracy is a crucial component of our calibration program. In most instances we cannot validate against fiducial locations. Therefore, we test various location metrics against known locations and assess the accuracy that each metric produces. Of the many potential metrics, we find that a network coverage criterion is the most applicable (Sweeney, 1998). Specifically, we find the azimuthal gap in station coverage to be the most important metric, followed by the number of stations used in the location. We present these criteria as a ratio (e.g. 50/90), where the first number (50) is the number of phases arrivals used in the location and the second number (90) is the largest azimuthal gap in station coverage (in degrees).

### **Calibration events derived from a teleseismic network (GT15)**

The relatively long period covered by global seismicity catalogs (e.g. ISC) provides numerous potential calibration events for use in regional calibration. However, assessing the accuracy of these events can be problematic because the seismic locations are typically the only locations available. In some instances, however, we have locations from other sources that allow us to compare the catalog epicenter with a much more accurate location. Sweeney (1998) compared teleseismic locations to accurate local network locations and found that a 50/90 criterion produced epicenters with 20-km accuracy (GT20). Myers and Schultz (2000) used updated local network locations and found that in all test cases teleseismic locations meeting 50/90 were within 15 km of the reference location (Figure 2).

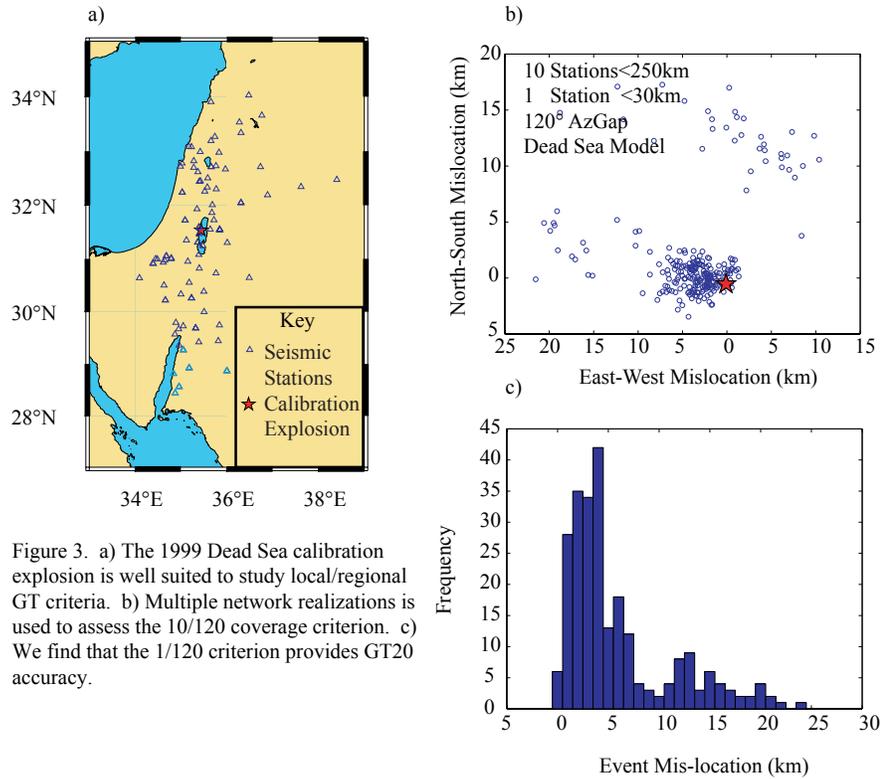


By applying the 50/90 criterion to teleseismic catalogs, we identify thousands of calibration events with good geographic distribution throughout Eurasia. Below, we describe criteria for local networks that can produce more accurate calibration events, but the geographic distribution of these events is poor compared to the 50/90 epicenters. By combining 50/90 events with more accurate calibration events, we obtain the high-quality travel-time calibration in limited areas and good calibration and uncertainty characterization over broad areas.

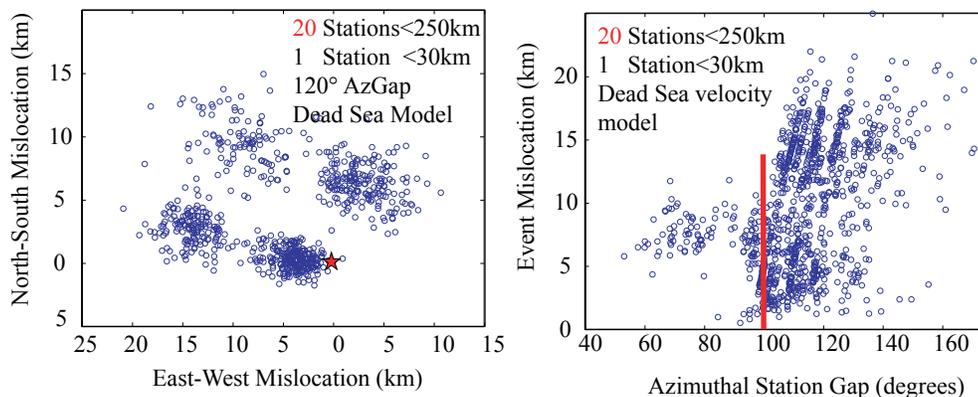
**Calibration events from a local-network (GT10)**

The most accurate, seismically constrained calibration events come from networks that are 1) close to the event and 2) contain numerous, well-distributed stations. The events can provide improved travel-time calibration because uncertainty associated with the event position is small. For convenience we apply the network coverage criteria (defined above) to local/regional networks.

Recently, a 10/120 local/regional coverage criterion was proposed for GT5 events (Bondar, personal communication), with all stations within 250 km and at least one station within 30 km. In order to test this criterion, we use the 1999 Dead Sea calibration explosions. These events are some of the select few events with fiducial locations that can be used to test epicenter accuracy for a dense local/regional network. There are about 50 stations of the joint Israel/Jordan network within 250km of the Dead Sea shots. To test the regional/local network location accuracy, we repeatedly sampled the network to meet the minimum 10/120 criterion. We located the explosion using 1000 random (non-redundant) network samplings to test the reliability of location accuracy under a variety of circumstances. We find that the resulting locations are accurate to 20 km at the 90% confidence level (Figure3). This test was conducted using a number of 1-dimensional velocity models – including IASPI91 and a local Israeli model (Shapiro, personal communication), and the results did not change significantly. It may be possible to improve upon the location with a 3-dimensional model. However, for the purposes of establishing coverage criteria, we want to minimize the influence of the velocity model because criteria that include the velocity model are not easily portable.



In order to establish a local/regional network criterion that improves upon the global network locations, we relocated the largest Dead Sea explosion 1000 times with variable network coverage (Figure 4). The results of this experiment show that – like teleseismic-network locations – azimuthal gap is the most important network coverage parameter, followed by the number of stations. When a 20/90 criterion is met, we locate the Dead Sea explosion to within 10 km of the known location. It is interesting to note that when all of the 50 stations are used, the location error can be as high as 5 km, depending on the velocity model used.



### **Coda Magnitude**

Magnitude estimation forms an integral part in any seismic monitoring endeavor, especially for nuclear explosion and treaty monitoring. Regional seismic discriminants used in nuclear explosion monitoring are often functions of magnitude such as  $m_b:M_s$ , high-to-low spectral ratios, and nuclear explosion yield estimation. Regional magnitudes used in discriminants for small-to-moderate sized crustal events using  $P_n$ ,  $P_g$ , and  $L_g$  all suffer from source and path heterogeneity. As a consequence, multi-station averaging is necessary to reduce the amplitude variability. For IMS monitoring, the average station spacing is larger than 1000 kilometers; thus, the ability to measure a stable magnitude for small-to-moderate-sized events becomes difficult because of limited numbers of stations and averaging of measurements. As a result magnitudes for small-to-moderate-sized events cannot be measured teleseismically and require a stable, single-station regional measure of earthquake size. We believe our methodology can provide a “universal” and transportable magnitude based on P and/or S coda that can be easily tied to the already established teleseismic catalogs.

### **Coda Magnitude Methodology**

Following a methodology outlined in Mayeda and Walter (1996), we apply a narrow-band filter for 13 frequency bands ranging between 0.03 and 8.0 Hz for the two horizontal components (Figure 5). This range of frequency bands is chosen such that we can compute  $M_w$ . We then take the  $\log_{10}$  of envelopes, average the two horizontal envelopes, then smooth them. After forming narrow-band envelopes for all the events, we measure the velocity of the peak S-arrival for each frequency band and plot versus distance. For the longest periods the peak corresponds to the Rayleigh or Love wave, but because we empirically correct for each frequency band, mixing wave types makes no difference on the final results. Since our goal was to calibrate both local and regional-distance earthquakes, we tried different functional forms that matched our data. We found that a simple hyperbola did an excellent job at simultaneously fitting the local and regional phase velocity,

$$v(x) = c0 - [c1/(c2 + x)] \quad (1)$$

where  $x$  is the distance and  $c0$ ,  $c1$  and  $c2$  are constants.

We found that a simple analytic form that resembles the single-scattering model of Aki (1969) generally does a good job at fitting the shapes of both regional and local coda envelopes. The main difference is that we had better fits by forming the envelopes relative to the direct S (or  $L_g$ ) arrival, not the origin time as is done in nearly all scattering models. The analytic expression that we used to fit the observed narrow-band envelopes at center frequency  $f$  is

$$A_c(f, t | x) = A_o \bullet H(t - \frac{x}{v(x)}) \bullet (t - \frac{x}{v(x)})^{-\gamma} \bullet \exp(-b \bullet (t - \frac{x}{v(x)})) \quad (2)$$

where  $A_o$  is a source constant,  $H$  is the Heaviside step function,  $t$  is the time in seconds from the origin,  $x$  is the distance in kilometers,  $v(x)$  is the velocity of the peak arrival in km/sec and  $\gamma$  and  $b$  control the coda decay. It should be noted, however, that the more complex 2-D and 3-D multiple-scattering models could also be used (see *Sato and Fehler* review, 1999). For our purposes we only want an empirical fit to the data over a range of distances and frequency bands and thus this simple form is completely adequate for this purpose. Furthermore, all the scattering models have implicit assumptions on the attenuation and geometrical spreading, assumptions we feel are inappropriate given that our data span both local and regional distances.

Since we are not explicitly applying a scattering model that has attenuation built into its formulation, we need to find an empirical distance relation for the coda amplitudes. This is preferable since we do not want to make any assumptions about homogeneous coda decay in a region – an assumption commonly made in past coda studies. Instead, we incorporate both geometrical spreading and attenuation (whether it stems from scattering, absorption, leakage etc.) using a strictly empirical form. We use Equation 2 as a means of matching the observed coda envelope shape to extract a coda amplitude measurement. In essence, Equation 2 is used as an empirical metric and thus any functional relationship that fits the data could have been used. The steps described here allow one to measure coda amplitudes, which are initially in dimensionless units, correct for distance and site effects and tie to an absolute measure. The validation of this approach is simple. We verify that we obtain the same source spectra at different stations and distances for the same event (thus confirming

our empirical distance corrections) and then verify that our inferred moments are comparable to those that were independently determined from other means such as long-period waveform modeling.

### **Coda Shape Factors**

Now that we know the velocities for each frequency band, we can fit our simple analytic form to find the coda shape parameter  $b$ , which controls the coda decay as measured from the direct S (or  $L_g$ ) arrival. By rearranging Equation 2 and taking the  $\log_{10}$  of both sides, we get

$$\log_{10} \left[ A_c(f, t|x) \cdot \left( t - \frac{x}{v(x)} \right)^y \right] = \log_{10} \left( A_o \cdot H \left( t - \frac{x}{v(x)} \right) \right) - b \cdot \left( t - \frac{x}{v(x)} \right) \cdot \log(e) \quad (3)$$

By plotting Equation 3 versus  $[t-x/v(x)]$  the slope of the best fitting line is  $b \log_{10}(e)$ .

Since we want to fit the coda at all distances, we try to measure the coda over a range of distances to determine if  $b$  is dependent upon distance. For the higher frequencies  $b$  is strongly distant dependent whereas for frequencies below  $\sim 0.5$  Hz the coda shape factor is roughly constant and is smaller (*i.e.*, decays more slowly than the higher frequencies). Again, we found that a simple form of a hyperbola fit the  $b$  values as a function of distance  $x$  spanning both local and regional distances.

### **Simple Distance Corrections**

For events in the Dead Sea rift and Gulf of Aqaba region, the Geophysical Institute of Israel routinely performs network locations and assorted magnitudes such as  $m_b$ ,  $M_L$  and  $M_w$ . Now that we have the velocities and coda shape factors we set  $A_o$  in Equation 2 to unity, take the  $\log_{10}$  to be consistent with our observed envelopes, then dc shift the synthetic envelopes to fit the observed envelopes using an L-1 norm. The magnitude of the dc shift is the non-dimensional coda amplitude. This amplitude is analogous to any direct wave measure in the sense that a distance and site correction are still required. Measuring the coda envelope amplitude over a length of time merely provides a more stable measure than using direct waves, which are of short duration and thus considerably more susceptible to interference, path heterogeneity, and source radiation pattern.

For each frequency band we subtract the network-averaged local magnitude,  $M_L(GII)$ , from the coda amplitude and plot versus distance in kilometers. We used events in a narrow magnitude range for each frequency band (*e.g.*, around  $\pm 0.25$  magnitude units) when determining the distance corrections to avoid potential biases related to corner frequency scaling. Figure 6 shows source-normalized coda amplitude (at 1 Hz) as a function of distance. We tried a number of classic attenuation relations that are routinely applied in direct-wave studies but found that the following empirical form,

$$A(f, x) = \left[ c1 + \left( \frac{x}{c2} \right)^{c3} \right]^{-1} \quad (4)$$

did the best job at simultaneously fitting local and regional distance coda, where  $x$  is the epicentral distance,  $f$  is the center frequency, and  $c1$ ,  $c2$ ,  $c3$  are constants. From Figure 6 we observe that the coda-derived amplitude at 1 Hz begins to decay at around 150-km distance, a likely result of local 3-D crustal scattering transitioning to guided 2-D  $L_g$ -coda at regional distances. This observation of constant coda amplitude in the local distance range has long been hypothesized in local S-wave coda studies of coda Q and site response. When we apply this to the broader region, we might expect different distant-dependent behavior such as velocity, coda shape factor and attenuation. These are elements of ongoing study.

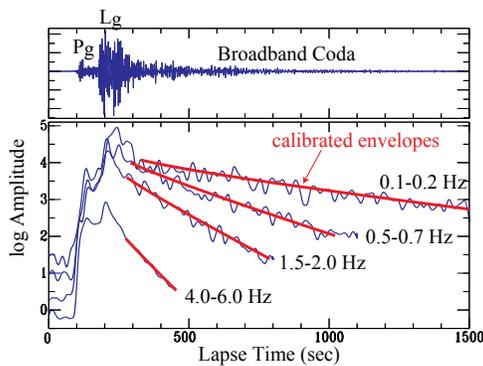


Figure 5. Example of a broadband waveform and selected narrowband envelopes (blue) along with calibrated synthetic envelopes (red).

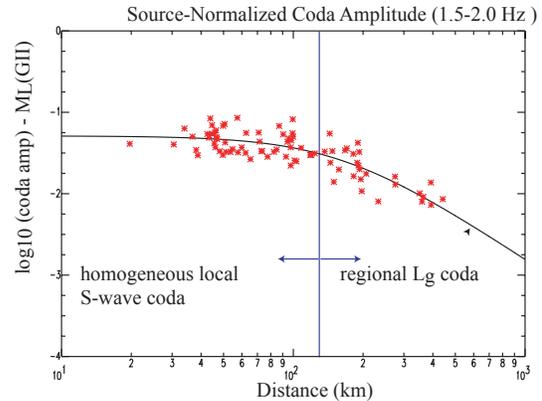


Figure 6. Source-normalized coda amplitudes for events of roughly the same  $M_L$ . Notice that the coda is roughly constant for the first 100 to 150 km and then begins to decay after this distance.

### Green's Function and Seismic Moment Corrections

Up to this point, we have measured non-dimensional coda envelope amplitudes and corrected for distance. In this section we relate these values to an absolute scale, namely seismic moment, to obtain a moment-rate spectrum. Our only assumption is that the S-wave source spectrum is flat below the corner frequency. We purposely underestimate where the corner frequency lies for our set of calibration events to avoid flattening our spectra unrealistically.

We used a 1-D reflectivity code to waveform model a series of moderate-sized earthquakes in the region to estimate seismic moment. This range of event sizes is needed to define the moment corrections ranging between  $\sim 0.03$  to  $\sim 2.0$  Hz, but larger Harvard CMT moments would only allow calibration of the lowest frequencies. As part of the spectral calibration, we add constants to all amplitudes for each frequency band such that the seismic moments, in a least squares sense, agree with the waveform modeled results. Since these are frequency-dependent corrections, independent of distance, the corrections must be uniformly applied to all distance-corrected amplitudes. Detailed analysis shows that with conservative estimates of the corner frequency, we can flatten the spectra for a range of event sizes. For events that are too small to be waveform modeled, we can still estimate moment using periods less than a few Hertz.

### Testing and Validation

Figure 7 shows spectra for two events, one is nodal at BGIO, and the other is not. In both cases, the spectra at KEG and BGIO are virtually identical, despite a significant source-radiation pattern difference. If we compare individual amplitudes for a large number of events, we also see that the inter-station variation is also very small. Finally, we verify that our absolute amplitudes are correct by computing  $M_w$  from the lowest frequencies of our measured spectra and compare against independent  $M_w$ 's from waveform modeling (note: we used different events than were used in the moment calibration step). Figure 8 shows that there is excellent agreement between the two approaches.

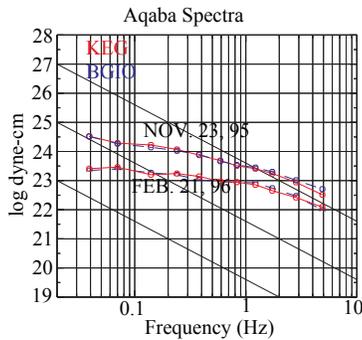


Figure 7. Spectra for two events recorded at BGIO and KEG are practically identical. Though the event of Nov. 23 is nodal at BGIO the averaging properties of the coda eliminate the radiation pattern.

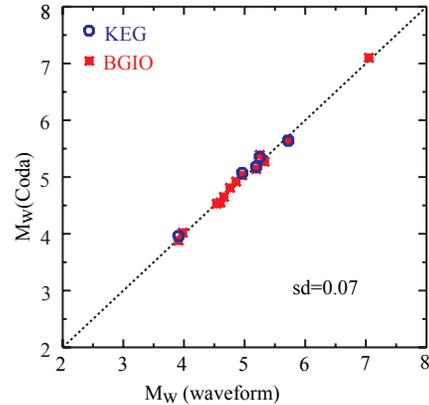


Figure 8. Our single-station coda-derived  $M_W$  estimates are in excellent agreement with waveform modeled events, comparable to results from the western United States.

## CONCLUSIONS AND RECOMMENDATIONS

Integration of calibration events from external contributors and LLNL's internal efforts requires rigorous validation procedures. We anticipate significant additions to the LLNL calibration database from work conducted under the NNSA ROA contracts. These efforts will provide new benchmark events for testing location accuracy criteria, as well as other events that will require criterion-based validation. The ROA efforts will also produce a catalog of coda-based magnitudes that will aid in subsequent monitoring studies.

We find a network coverage criterion to be best suited for epicenter accuracy validation. For events determined with a teleseismic network we use the 50/90 criterion of Sweeney (1998). After revision of benchmark events, we find that the 50/90 criterion provides 15-km accuracy as opposed to the 20-km accuracy reported by Sweeney. For local networks we test the 10/120 criterion of Bondar (personal communication), and find that this criterion provides 20-km accuracy. By increasing the number of network stations to 20 and reducing the azimuthal gap to  $90^\circ$ , we find that accuracy can be improved to 10 km.

We have developed a code-based magnitude determination that is particularly applicable to sparse regional networks. The method is based on simultaneous analysis of narrow-band coda envelopes. Raw amplitude observations are calibrated using waveform modeling results for large events and assuming a simple source spectral model. We provide tests demonstrating the robustness of the method and favorable comparisons to independent waveform modeling results.

## REFERENCES

- Aki, K. (1969). Analysis of the seismic coda of local earthquakes as scattered waves, *J. Geophys. Res.*, **74**, 615-631.
- Mayeda, K., and Walter, W. (1996). Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes, *J. Geophys. Res.*, **101**, 11195-11208.
- Myers, S.C. and C.A. Schultz (2000). Improving sparse network seismic location with Bayesian Kriging and teleseismically constrained calibration events, *Bull. Seism. Soc. Am.*, **90**, 199-211.
- Myers, S.C. and C.A. Schultz (2000). Evaluating Reference Events for Seismic Event Location, UCRL-JC-143948 Abs.
- Schultz, C.A., S.C. Myers, J. Hipp, and C.J. Young (1998). Nonstationary Bayesian kriging: A predictive technique to generate spatial corrections for seismic detections, location, and identification, *Bull. Seismol. Soc. Am.*, **88**, 1275-1288.
- Sweeney, J. (1998) Criteria for selecting accurate event locations from NEIC and ISC bulletins, UCRL-JC-130655, 1998.